Raman compensation for a two-channel soliton-based optical fiber communication system

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A technique of Raman compensation for a two-channel soliton-based fiber communication system is introduced. By fixing the wavelength spacing between two channels, one can calculate the pumping wavelength and intensity in such a way that balance between loss and gain is reached for each channel. In this computation the Raman conversion between two channels plays an important role in simultaneous compensation for both channels.

Soliton transmission has been proposed to achieve high-bit-rate fiber communication systems.[1] Distortionless short pulses can be propagated along the fiber because of the balance between the effects of dispersion and of self-phase modulation. In the presence of fiber loss, however, the pulse intensity decays, resulting in weakened self-phase modulation effects and therefore in destruction of the soliton. To solve this problem, loss-compensation techniques that use stimulated Raman scattering have been introduced.[2,3] In such a technique cw pump waves are injected periodically into the fiber so that the decaying signal pulses are amplified during propagation along the fiber. Stable transmission of short solitons over 1000 km of fiber can be obtained.[4] However, only single-channel transmission was studied extensively. Simultaneous Raman compensation for multiple channels must be completely understood if the wavelength-multiplexing technique is to be used. In this Letter we investigate the Raman compensation in a two-channel system in which Raman conversion between two channels is important. Although the technique of Raman compensation for multiple channels was briefly discussed in some earlier publications,[3,4] our research in this Letter provides, for the first time to our knowledge, clear choices of various pumping parameters, such as the pump intensity and pump wavelength, for simultaneous compensation for both channels. In this research a polarization-preserving fiber is assumed to be used.

The basic idea of compensation for two-channel solitons follows that for compensating for one-channel systems introduced by Hasegawa[2] and used by Mollenauer *et al.*[3] Nevertheless, in the case of two channels, the Raman conversion between two channels must be taken into account. Let q_m represent the normalized complex pulse envelope for channel m ($m = 1, 2$). We assume that the central frequency of q_1, ω_{01}, is higher than that of q_2, ω_{02}. When the central-frequency separation between two channels is much larger than the bandwidth of the signals, the coupled equations governing wave propagation can be written as

$$\frac{\partial q_m}{\partial \zeta} + \delta_m \frac{\partial q_m}{\partial \tau} - K_m \frac{j}{2} \frac{\partial^2 q_m}{\partial \tau^2} = j x_m q_m (|q_m|^2 + 2|q_n|^2) - \frac{\Gamma_m}{2} q_m + \frac{\alpha_m}{2} I_p q_m + (-1)^m \frac{\alpha_{R_m}}{2} |q_n|^2 q_m, \quad m, n = 1, 2, \quad m \neq n. \quad (1)$$

Here $K_1 = 1$ and $K_2 = k_{02}''/k_{01}''$, where $k_{0m}'' = \partial^2 k/\partial\omega^2|_{\omega_{0m}}$, $m = 1, 2$. Note that the difference between δ_1 and δ_2 represents that of group velocities between two channels and leads to the pulse walk-off. The self-phase and cross-phase modulations are represented, respectively, by the terms $j x_m q_m |q_m|^2$ and $2 j x_m q_m |q_n|^2$, $n \neq m$, where x_m is a constant close to unity. Because of the difference of central wavelengths between two channels, x_1 is slightly different from x_2. Also, Γ_m ($m = 1, 2$) denotes the linear losses in the fiber, α_{Rm} represents the coefficients of Raman conversion between two channels, and α_m stands for Raman gain coefficients from the external pump intensity I_p. In obtaining Eq. (1) we used variables transformation for the normalized distance ζ, time τ, and amplitude q_m, $m = 1, 2$, similar to those in Ref. 2. At the wavelength 1.5 μm, $\zeta = 1$, $\tau = 1$, and $q = 1$ correspond to a 15-km length, a 19-psec time period, and a 7.2×10^5 V/m electric field strength, respectively.

From the right-hand side of Eq. (1) it can be seen that the pump power to channel 1 is used for compensating not only for the linear loss but also for the nonlinear loss due to Raman conversion. In this sense, the pulses in channel 2 have two contributions to compensation for the linear loss: one from the external pump wave and the other from channel 1 that is due to Raman conversion. On the other hand, the pump intensity will decay along the fiber because of the linear loss and depletion by pumping channels 1

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and 2. We have the following equation for the pump intensity I_p (Ref. 2):

$$\frac{dI_p}{d\zeta} = -\Gamma_p I_p - \alpha_1 I_{10} I_p - \alpha_2 I_{20} I_p, \qquad (2)$$

where Γ_p is the loss rate at the wavelength of the pumping wave. Also, I_{m0} is the average soliton intensity of channel m, given by

$$I_{m0} = \frac{1}{2T} \int_{-T}^{T} |q_m|^2 d\tau, \qquad (3)$$

with $2T$ representing a bit period. Note that in writing Eq. (3) we have assumed that a soliton exists in every bit. This is naturally not true in a digital communication system. We believe that a more sophisticated pumping scheme will result from future studies based on our results in this Letter. The solution for Eq. (2) can be obtained easily:

$$I_p = I_{p0} \exp(-G_p \zeta), \qquad (4)$$

with

$$G_p = \Gamma_p + \alpha_1 I_{10} + \alpha_2 I_{20}, \qquad (5)$$

where I_{p0} is the input pump intensity. If we use both downstream and upstream pump waves, the integrated pump gain over an amplification period ζ_0 for the pulse intensity in channel m is

$$g_m = \frac{2I_{p0}\alpha_m}{G_p} [1 - \exp(-G_p \zeta_0)]. \qquad (6)$$

Therefore simultaneous compensation for both channels can be achieved if the following equation is satisfied:

$$\frac{2I_{p0}\alpha_m}{G_p} [1 - \exp(-G_p \zeta_0)] = [\Gamma_m - (-1)^m \alpha_{Rm} I_{n0}]\zeta_0, \quad m, n = 1, 2, \quad m \neq n. \qquad (7)$$

Note that in obtaining the second term on the right-hand side of Eq. (7) we have taken the effect of walk-off between two channels into account.[5] It has been shown that the Raman conversion per unit length is affected by the wavelength separation between two channels only through the difference in the Raman coefficients α_{R1} and α_{R2} but not through the walk-off effect. This point will be discussed in detail in another publication.

Equation (7) is to be solved for several required pump parameters, such as the pump intensity I_{p0}, Raman coefficients α_1, α_2, α_{R1}, and α_{R2}, and amplification period ζ_0. Note that the Raman coefficients depend on the wavelength difference between the pump and Stokes waves. In what follows we assume that the central wavelengths of those two channels are given, and we intend to evaluate the aforementioned parameters for simultaneous compensation for both channels. To this end, Eq. (7) produces

$$\alpha_1(\Gamma_2 - \alpha_{R2} I_{10}) = \alpha_2(\Gamma_1 + \alpha_{R1} I_{20}). \qquad (8)$$

The dependence of the Raman gain coefficient on the frequency difference between two waves is shown by the solid curve in Fig. 1.[6] This curve can be used for solving Eq. (8). However, to simplify the computation an approximate curve, shown as the dashed curve in Fig. 1, is used. In this approximate curve, a linear function is used on the left-hand side to a peak value at 440 cm^{-1}; and on the right, to the peak value, an exponential decay given by $\exp[-b(\Delta - 440)]$ is assumed, with b equal to 5×10^{-3} cm. By using this dashed curve and assuming that $\Delta_{p1} = (1/\lambda_p - 1/\lambda_1)$ and $\Delta_{12} = (1/\lambda_1 - 1/\lambda_2)$, with λ_p, λ_1, and λ_2 the wavelengths of the pump wave and channels 1 and 2, respectively, we can reduce Eq. (8) to

$$\frac{\Delta_{p1}}{440} (\Gamma_2 - \alpha_{R2} I_{10}) = \exp[-b(\Delta_{p1} + \Delta_{12} - 440)](\Gamma_1 + \alpha_{R1} I_{20}). \qquad (9)$$

Note that Δ_{p1} and Δ_{12} in Eq. (9) are in inverse centimeters. Equation (9) can be solved numerically for Δ_{p1}. Once Δ_{p1} is calculated, α_1 and α_2 can be evaluated. Then the required input pump intensity I_{p0} can be evaluated through Eq. (7). Note that the amplification period ζ_0 is usually left to the designer's choice.

To show that the analysis above is valid, we offer the following numerical simulation. Equation (1) is solved by using the beam-propagation method.[7] The channel wavelengths are set at 1.5 and 1.51 μm. A bit rate of 2.9 GHz, with a FWHM of a one-soliton pulse occupying ~10% of the bit period, is assumed for both channels. In this situation the interaction between neighboring solitons in either channel is negligibly weak. Since the two-channel wavelengths are close, we choose the same loss rate of 0.18 dB/km. Then, from Fig. 1, we read $\alpha_{R1} \approx \alpha_{R2} = 0.05$. In the next step, the pump wavelength can be evaluated from Eq. (9) to give 1.41 μm, and hence α_1 and α_2 can be read to give $\alpha_1 = 0.491$ and $\alpha_2 = 0.483$. We set the amplification period equal to $\pi/2$, corresponding to 23.6 km in real

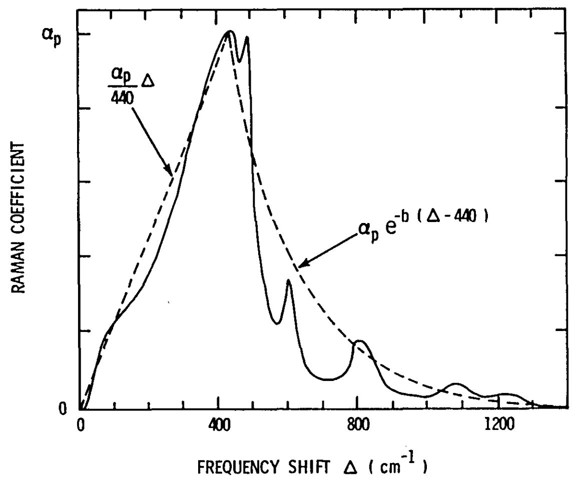

Fig. 1. Raman gain coefficient of a silica-core fiber. The peak value is $\alpha_p = 1.86 \times 10^{-11}$ cm/W at 440 cm^{-1} for the frequency shift when the pump wavelength is $\lambda_p = 0.532$ μm. The Raman gain coefficient varies with the pump as $1/\lambda_p$. The solid curve represents experimental data from Ref. 6, and the dashed curve is an approximation for our analysis.

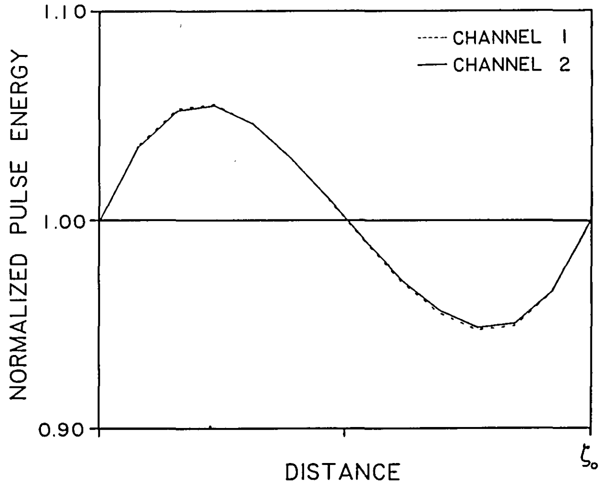

Fig. 2. Evolution of the normalized energy of the pulses in channels 1 (dashed) and 2 (solid). At the end of an amplification period, i.e., a normalized distance of $\pi/2$, the energy is recovered.

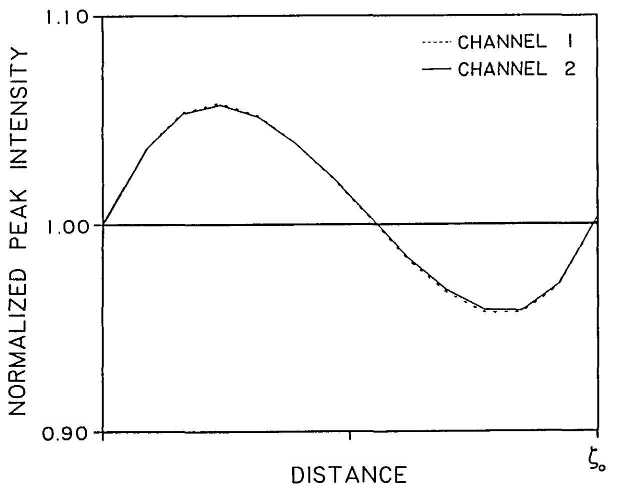

Fig. 3. Same as Fig. 2 except that the evolution of the normalized peak intensity is shown.

distance. A loss rate of 0.5 dB/km is assumed for the pump wave. Therefore the pump intensity I_{p0} can be calculated by using Eq. (7). The result is $I_{p0} = 1.963$. With the calculated parameter values $\delta_1 = -77.9$, $\delta_2 = 77.9$, $x_1 = 1.003$, and $x_2 = 0.997$, we are ready to solve the coupled Eq. (1) numerically. In Figs. 2 and 3 we show the evolutions of pulse energy and peak intensity, both normalized by the individual initial values. In these figures the dashed curves describe the evolution of a pulse in channel 1; solid curves describe that of a pulse in channel 2. We can see that solitons in both channels are substantially recovered at the end of an amplification period. Only a 0.3% deviation from the input peak intensity is found for both channels. We have also obtained the evolution of the pulse area, indicating complete compensation, except for only slight deviations, for both channels.

In conclusion, we have shown a simultaneous compensation scheme for a two-channel wavelength-multiplexing, soliton-based optical fiber communication system. Numerical simulations have demonstrated stable propagation of solitons in both channels over an amplification period. It is hoped that compensation for systems with more than two channels can be designed based on the concept and results in this Letter. As we have shown above, in one amplification period some slight distortions of solitons are observed. In our future research this compensation scheme for many amplification periods will be studied. Larger distortions are expected. Note that in our numerical case the cross-phase modulation is negligibly small over one amplification period. Since this effect is a cumulative one, it may play an important role when many amplification periods are required. The significance of Raman conversion can be seen from the difference between the values of α_1 and α_2. This difference, although small, is important in this compensation scheme. Meanwhile, it is shown that in an amplification period the total Raman conversion between two channels is affected by the wavelength separation only through the variations of Raman coefficient. Also, Brillouin scattering must be included when the pump intensity is strong.[8] Finally, we must mention that the approximation in Fig. 1 may be rough. For a more precise result, a more accurate curve must be used.

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